A REVIEW OF METHODS FOR DEVELOPING ACCELERATED TESTING CRITERIA

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ABSTRACT

Accelerated vibration testing seeks to compress long service exposures to vibration into a reduced length laboratory test by increasing the amplitude and/or frequency of the applied inputs during the laboratory test relative to the amplitude and/or frequency experienced during service. This testing procedure provides an important tool that can reduce testing time associated with a new design and reduce time to market. This paper will summarize current methods that are employed to develop accelerated testing criteria and will highlight the attributes and limitations of these methods. Typically there are two ways of accelerating vibration testing. The first method involves testing at fewer cycles but at higher amplitude levels; and the second method involves testing at higher frequencies (rates). A combination of the two is also an option. Development of an accelerated test based on either of these methods requires *a priori* knowledge of the controlling failure mechanisms. The review will begin with a discussion of Miner's Rule for developing accelerated testing criteria. This rule, which is based on a linear damage accumulation assumption, was first proposed in the 1940's for fatigue failures of ductile metals loaded repetitively in bending. Confounding factors associated with developing accelerated testing criteria for nonlinear vibration response (e.g., rattling of components) will be illustrated with an example.

1. INTRODUCTION

The theme of this year's IMAC is "Applied Modal Analysis: Reducing Time to Market." Systems that are subject to repetitive long-term vibration environments, such as aircraft and automotive structures, may accumulate mechanical damage that adversely affects their performance characteristics. Accelerated vibration testing seeks to compress long service exposures to vibration into a reduced-length laboratory test that generates an equivalent level of damage as the actual service environment. Clearly, the development of methods for establishing accelerated vibration test criteria and *a priori* prediction of the associated system deterioration are needed so that meaningful accelerated tests can be specified.

Coupled with accelerated testing and aging is the need to continually monitor the progression of damage, so that the onset of damage and the remaining life of the tested structure can be evaluated. In the case of automobile body rattling, this monitoring may entail simply listening to the noise level to determine at what point in the accelerated testing process the rattling has become unacceptable. For other structures, damage is not so easily evaluated. In cases of internal damage to a complex component, vibration-based damage-identification methods could be employed, possibly using the same excitation source as used in the accelerated testing process.

The purpose of this paper is to examine methods for the development of accelerated vibration testing criteria, coupled with a brief discussion of methods to evaluate the associated progression of the damage. This paper is restricted to aging of products caused by vibration environments. Other environments or mechanisms of product aging, e.g., thermal cycling, are not addressed here.

Vibration-based accelerated testing can be partitioned into the following four steps:

1. **Assessment of Vibration Environments:** The first step in defining accelerated testing criteria is to make an assessment of the vibration environment that must be accelerated. This assessment includes examination of the amplitude and frequency content of input signals, the nature of the signals, e.g., random or steady-state, the order in which such signals are applied, and quantification of variability that can expected in these vibration environments. The description of the vibration environment may be probabilistic rather than deterministic. In some cases direct measurements of the vibration environment may exist, while in other cases the vibration environments may have to be extrapolated based on assumptions regarding future system performance.

2**. Identification of Failure Mechanisms:** To accurately specify an accelerated test sequence, it is essential to identify the particular failure mechanism(s) to be accelerated. Failure mechanisms may be caused, for example, by fatigue, wear, or rattling and repeated impact. Also, parameters to which these failure mechanisms are sensitive should also be examined. As an example, damage accumulation from repeated impact could be sensitive to the initial gap between parts.

3. **Identification of a Damage Accumulation Rule and Specification of an Accelerated Test Sequence:** Condensation of the vibration histogram will ultimately be based on a damage accumulation rule. Miner's Rule, corresponding to a linear damage accumulation assumption as summarized in Fig. 1, is often selected for its simplicity; but improvements on this rule have been reported that better mimic reality. Often associated with the damage accumulation rule is the need for editing the acceleration histogram. This editing is another process by which the histogram of input vibration amplitudes is condensed. As an example, perhaps a portion of the response amplitudes for a steel component are below the fatigue limit, such that these low-level vibrations do not contribute to fatigue damage. These inputs could then be discarded to condense the histogram before time-compression based on the damage accumulation rule is employed.

4. **Monitoring and Verification:** One particular downside of accelerated vibration testing is the risk of artificially accelerating the wrong failure mechanism. Tests are needed to verify that the accelerated histograms accurately reproduce the desired levels of damage. However, economic concerns often make such tests impractical or impossible. Further, for determining the expected life of a product, it is essential that the product continually be monitored for the onset of damage throughout the accelerated test program.

2. CLASSIFICATION OF ACCELERATED VIBRATION TESTING

Accelerated vibration testing has been applied to a variety of different products, as it is often infeasible to test a product in real time over its entire life before placing the product on the market. Accelerated testing therefore involves a temporal compression of the testing process. One way to classify accelerated vibration testing is in the manner in which this compression is performed. An examination of recent practical examples of accelerated vibration testing illustrates four potential methods:

a. Increase vibration input amplitudes above normal level;
b. Edit field data and use most severe observed amplitudes;
c. Find the operating condition that led to observed rapid damage growth and operate continuously at that level; or
d. Increase the frequency of the applied forcing function.

The above four potential methods fall into three general categories: Methods a involves modification of the applied vibration amplitude (testing for fewer cycles); Methods b and c involve deleting cycles that have little or no influence on the accumulation of damage; and Method d involves the increase of the applied forcing frequency (testing for the same number of cycles, but at higher rates). Combinations of these methods are also an option. Development of accelerated tests based on any of these methods requires *a priori* knowledge of the controlling failure mechanisms. In addition, strain-rate effects and the influence of other vibration modes on the test specimen must be understood if testing at higher frequencies is to be employed. Further, there are confounding factors associated with developing accelerated testing criteria for nonlinear vibration response (e.g., rattling of components). In all cases, however, the underlying principle is that the damage accumulated by the failure mechanism of interest is the same for service and accelerated testing conditions.

Examples of each of these methods are as follow:

a. ABOVE OPERATING RANGE: Lambert (1990) reports on accelerating the Gaussian random vibration testing of electronic black boxes. The test duration is typically compressed by a relatively large factor (e.g., 1000), coupled with an *increase* in the applied vibration level over that experienced in service. The test duration is a function of the material type of the critical structural element.

b. AT MAXIMUM OPERATING RANGE: Hurd (1991,1992) describes an accelerated automotive squeak and rattle performance evaluation. This testing, performed for the equivalent of 100,000 miles of durability cycling, was completed in a 15-day period. Tests were performed with a partial-vehicle model mounted on a multi-axis shaker table. Excitation was based on an editing process applied to recorded field data. The field data with the highest energy content were retained. Thus accelerated vibration testing was based on the most severe *observed field data.* Four squeak and rattle evaluations were performed at various stages in the testing process by exciting the partial vehicle with various specified vibration excitations while a person sitting in the vehicle made subjective noise observations.

c. BELOW MAXIMUM OPERATING RANGE: Krivoy, et al. (1986) report an accelerated testing study to investigate piston ring groove wear in heavy duty diesel engines. The investigation sought to both reproduce excessive wear observed on fielded parts, as well as to produce this wear in a much shorter period of time. The particular operating point resulting in the maximum rate of piston-ring wear was quite different from the full-rated power condition at which the engines were normally tested to verify durability. Therefore, operating the system at this critical point, which was below the maximum amplitude level, was used to accelerate the testing.

The above three categories involved classification of methods by relative *amplitude* of the applied test signal or excitation. In cases where the input signal is a single-frequency sinusoid, the possibility of increasing the *frequency* to accomplish accelerated aging can also be employed, as long as the applied excitation frequency is well below the lowest normal mode of vibration of the tested system. Therefore, a fourth category of classification might be:

d. TESTING AT HIGHER FREQUENCY: An example here would be a component subjected to a low-frequency shipboard vibration environment (say 20 Hz. sinusoidal). If the first mode of the component of interest were, for example, 300 Hz, then, depending on damping, a factor of 10 increase in the test frequency, without an amplitude change, would reduce the total test time by the same factor. Increasing the magnitude of the input signal appropriately could be used to further compress the test time.

In all cases the question that must be answered is: What are the simulated test conditions which will "equal" a lifetime of actual product use? This review will begin with a discussion of Miner's Rule for developing accelerated testing criteria. This rule, which is based on a linear damage accumulation assumption, was first proposed in the 1940's for fatigue failures of ductile metals load repetitively in bending. Nonlinear improvements to this rule will be briefly outlined. Confounding factors associated with developing accelerated testing criteria for nonlinear vibration response (e.g., rattling of components) will be illustrated with an example.

3. ANALYTICAL MODELS FOR PRODUCT LIFE ESTIMATION AND ACCELERATED LIFE TESTING

3.1 Miner's Rule

Miner's Rule has formed the primary basis for vibration-based accelerated life testing in the past and remains attractive because of its simplicity. Miner's Rule is based on a cumulative fatigue damage mechanism of failure and is fully discussed by Shigley (1977) and Collins (1993). The original idea was that fatigue damage curves were available for a material subjected to a single reversed stress, s, for n cycles. Miner's Rule then provided a way to relate this to more realistic cumulative loadings of s_1 for n_1 cycles, s_2 for n_2 cycles, etc. As expressed by Caruso and Dasgupta (1998) in a recent overview of accelerated testing analytical models, the fraction of the product life used, FPL, is a linear combination of all j damage increments,

$$FPL= (n_1/N_1) + (n_2/N_2) + ...+ (n_j/N_j) \quad (1)$$

where
n_i = Number of cycles at a particular stress level; and
N_i = Number of cycles to failure at the same stress level.

Assumptions associated with Equation (1) are that all damage increments add together independently, regardless of the damage mechanisms involved, that is, synergistic effects are ignored. Another assumption is that the specified input parameter, often acceleration in a vibration test, can be directly related to the induced stress level and the number of stress cycles. Also, failure is assumed to be independent of the order in which the cycles are applied. Further, the implication is that the failure mechanism of the particular structural element of interest is fatigue related. Shigley (1977) and Caruso and Dasgupta (1998) bring out additional limitations of this class of methods. Equation 1 is generally applicable to ductile metals.

3.2 Nonlinear Cumulative Damage Theories

Collins (1993) presents a detailed discussion of a variety of cumulative fatigue damage theories that have been introduced as refinements and extensions of Miner's Rule. The various nonlinear theories attempt to incorporate observed effects such as the nonlinear accumulation of fatigue damage not accounted for in the linear Miner's Rule. Again, the idea is to predict fatigue life in components subjected to variable amplitude stress using constant amplitude stress data.

The Marco-Starkey Cumulative Damage Theory (Marco and Starkey, 1954) attempts to account for the experimentally observed nonlinear relationship between damage and cycle ratio by introducing damage curves for each level of completely reversed sinusoidal stress as

$$D = [n / N]^{m_i} \quad (2)$$

where m_i is a function of the stress level. Curves of damage fraction, D, versus cycle ratio, n/N, are first plotted as a function of stress level. The sequence of

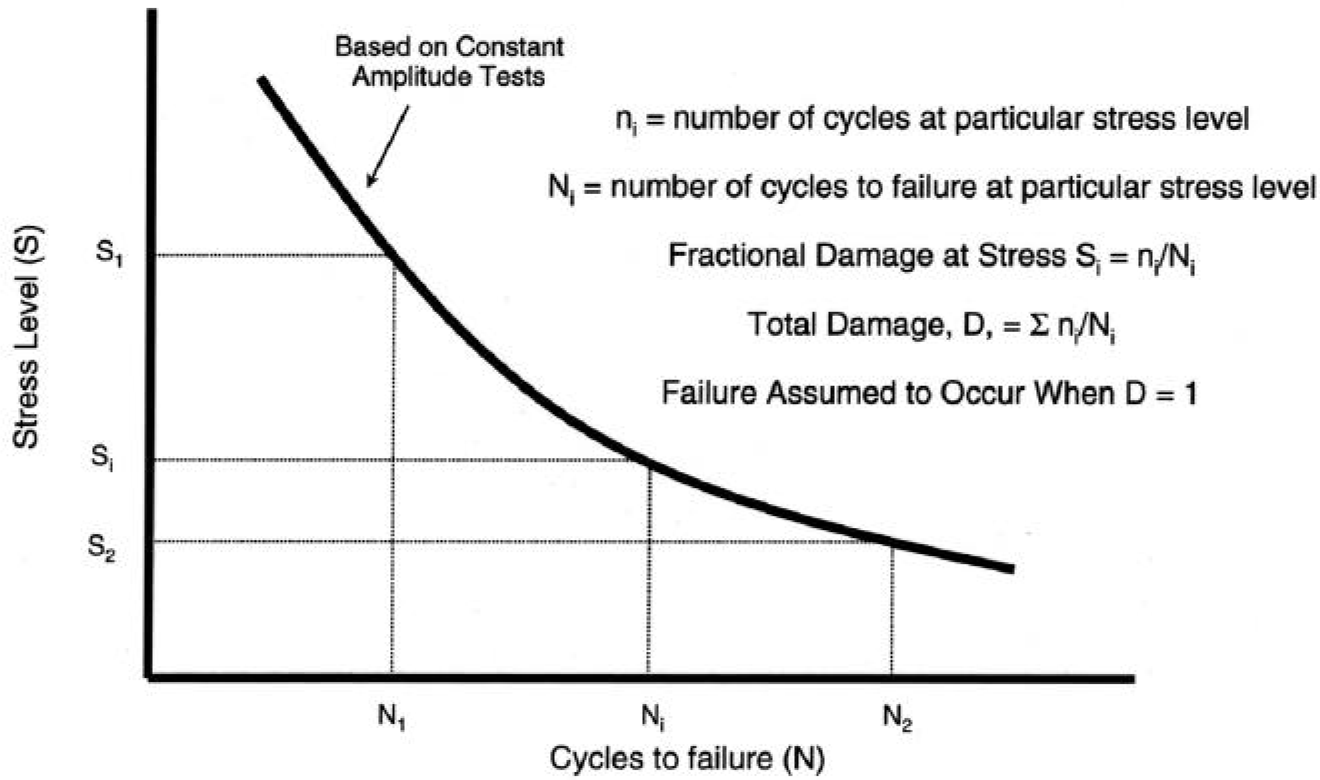

Figure 1. Miner's Rule for damage accumulation.

operating stress levels is then used in a simple graphical procedure, proceeding along the proper curves until D=1 is reached. Significantly different results are achieved with different sequences of loading, better mimicking experimentally observed behavior than Miner's rule. The procedure collapses to Miner's Rule for all $m_i = 1$.

Henry (1955) proposed a cumulative damage theory based on the principle that the S-N curve is shifted as fatigue damage accumulates. A procedure is introduced to extend the method to a sequence of different applied stress cycles. Gatts (1961) developed a closely related theory, but included a continuous change in the fatigue strength and fatigue limit with application of stress cycles.

Corten and Dolan (1956) incorporate six specific assumptions related to the nucleation of fatigue damage and its propagation. They developed a simple expression for estimating the number of cycles to failure for repeated blocks of many different stress levels in terms of a material constant, d, appearing as an exponent in a power law relation. Marin's theory (1962) accounts for the relationship between damage as a function of cycle ratio and changes in the S-N curve caused by damage accumulation. It can be shown to reduce to the Corten Dolan theory for equal exponents, d, and to collapse to Miner's Rule for certain parameter values.

Finally, Grover (1960) partitions the fatigue process into two phases, a crack initiation phase and a crack propagation phase, each with a linear damage rule. However, he did not provide a method for defining the ranges of these two phases. Later Manson, et al. (1967) introduced the "Manson Double Linear Damage Rule" that proposed an empirical technique for establishing the range of the crack initiation and propagation phases as well as the associated damage equations.

All the above approaches to accounting for cumulative damage at varying load levels all are specifically directed toward metal fatigue. There are, of course, numerous other failure mechanisms caused by a long-term vibration environment that one may wish to accelerate.

4. INVERSE POWER-LAW MODELS

The Coffin-Manson model described by Caruso and Dasgupta (1998) is a representative example of Power-Law Models for accelerated testing. The required number of cycles at acceleration level g_2, $N(g_2)$, that corresponds to an equivalent amount of damage to $N(g_1)$ cycles at acceleration level g_1 is

$$N(g_2) = N(g_1)\,(g_1/g_2)^{\beta} \qquad (3)$$

where
β = exponent based on material and damage mechanism.

The exponent, beta, represents a fatigue characteristic of a particular material, as derived from the slope of the S-N curve for that material. As noted by Caruso and Dasgupta, beta is a function of both the material and the damage mechanism. Typical beta values for ductile metals are reported as β = 5-6 for vibration. This relation is used in MIL-STD-810C-F, Method 514. Similar laws are applied to temperature cycling fatigue testing, although values of beta are different from accelerated vibration testing.

5. SOME EXAMPLES OF ACCELERATED TESTING

5.1. Multi-DOF Linear Vibration System

Consider an n-DOF linear spring-mass system. There are n normal modes of vibration. Linearly increasing the level (magnitude) of excitation will increase the system response (accelerations, stresses) linearly without changing the form of that response (e.g., the relative modal response will be the same). Therefore, accelerated aging could be accomplished with a change in input excitation magnitude.

If the excitation were a single sinusoidal input to the system with frequency well below the first natural frequency, then the possibility exists for increasing frequency of the input to enhance the aging process as well. A combination of magnitude and frequency increases might be another possibility in that case.

5. 2. Impact-Dominated Vibrations

Consider the impact dominated, vibrating, single DOF system shown in Fig. 2. The system consists of a hollow outer mass containing a freely sliding inner mass. The system is a representative simplification of impact/rattling systems. The outer mass is subjected to a prescribed sinusoidal displacement-time history

$$S(t) = A[\sin(\omega t+\phi)+1] \tag{4}$$

Where
A= displacement amplitude of the outer shell motion,
ω = prescribed driving frequency, and
ϕ = phase.

The prescribed displacement has been given a unit shift to the right so that displacement of the outer mass is never negative.

Impacts can occur at either left or right ends of the model in Fig. 1 at the instant when one of the respective gaps (δ_1 or δ_2) go to zero. There is a total rattle space, δ, of

$$\delta = \delta_1 + \delta_2 \tag{5}$$

the inner mass at time t=0 is subjected to initial displacement and velocity conditions x_1 and v_1, respectively. In terms of the kth impact, the position of the inner mass at time t, x(t),is given by

$$x(t) = x_k + v_k(t - t_k) \tag{6}$$

where x_k is the position of the inner mass at the k^{th} impact and t_k is the corresponding time. Note that k=1 corresponds to the initial condition, so the first actual impact occurs for k = 2.

The range in position, x*, of the inner mass relative to the outer mass lies between 0 and δ. Impacts occur when x* goes to zero or x* goes to δ. For a "left" impact,

$$d_L(t) = x(t) - s(t) = 0 \tag{7}$$

For a "right" impact

$$d_r(t) = s(t) + \delta - x(t) = 0 \tag{8}$$

Here, $d_L(t)$ and $d_R(t)$ are functions selected such that they are positive definite, and take on a value of zero only when impact occurs.

The first time for which $d_L(t)$ or $d_R(t)$ approaches zero, t > t_k, defines the time of the next impact. Thus the time, t_{k+1}, of the next impact is given by the minimum time, t, t > t_k of the two expressions below:

$$d_L = 0 = x(t) - s(t) = x_K + v_K(t - t_k) - A[\sin(\omega t + \phi) + 1] \tag{9}$$

$$\begin{aligned} d_R = 0 &= s(t) + \delta - x(t) \\ &= A[\sin(\omega t + \phi) +1] + \delta - [x_k + v_k(t - t_k)] \end{aligned} \tag{10}$$

The impact velocity of the inner mass is determined using the definition of the coefficient of restitution and the concept of a kinematic reference frame as

$$v_k = (1 + \varepsilon)u_k - \varepsilon v_{k-1} \tag{11}$$

Where
v_k = velocity of the inner mass following collision,
v_{k-1} = velocity of the inner mass just before collision,
u_k = instantaneous velocity of the outer mass, and
ε = coefficient of restitution.

The above equations were solved numerically for one set of baseline input parameters. The baseline response, taken out a total of ten impacts is shown in Fig. 3. The position of the left and right inner surfaces of the outer mass are indicated by the thin solid and dotted lines, respectively. The vertical distance between these lines is the rattle space available for the relative motion of the inner mass.

A seen in Fig, 3, the position of the inner mass is initially constant until, at t = 0.32, a left-side impact occurs. A second left-side impact occurs at t = 1.0, followed by a sequence of two right side impacts, two left side impacts, two right side impacts and, finally, two left-side impacts.

It is interesting to investigate the influence of small changes of numerical values of the input parameters on

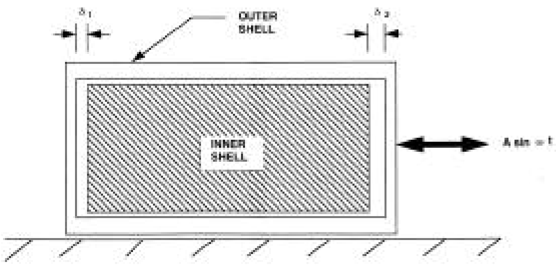

Figure 2. Simplified one-dimensional model of impacting/rattling shells.

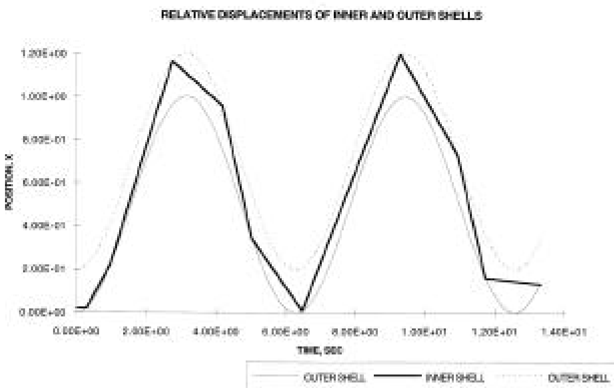

Figure 3. Baseline case of ten impacts.

the solution outcome. Consider a five-percent increase in the rattle space as shown in Fig. 4. After the first cycle, the response becomes totally different. This behavior is an illustration of the sensitive dependence to initial conditions, a property often associated with systems exhibiting chaotic behavior.

In Fig. 5, the clearance is varied over a range $\delta = 0.05$ to 0.3. Other parameters are $A = 1.0$, $\phi = -\pi/2$, $\varepsilon = 0.8$, and $\omega = 10$. Many impact cycles are considered at each clearance value evaluated. The position of the inner mass at the time of collision is indicated in Fig. 5. It should be noted that even though the system is chaotic, the structure of the above plot does not change with initial conditions. As can be seen in Fig. 5, there exist numerous chaotic and periodic regions as the clearance varies.

Using the above simplified impact/rattling model, the possibilities of accelerated testing were investigated. Two methods of accelerating the testing were examined: increase in amplitude or increase in frequency. Preliminary results for one set of parameters reveals that

1. Increasing the **amplitude** of the motion of the outer mass affects the fundamental (chaotic/periodic) impact behavior of the system. Accelerated aging by increasing

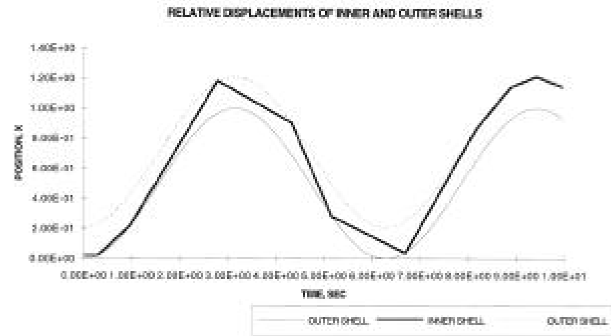

Figure 4. Influence of five-percent increasse in total rattle space.

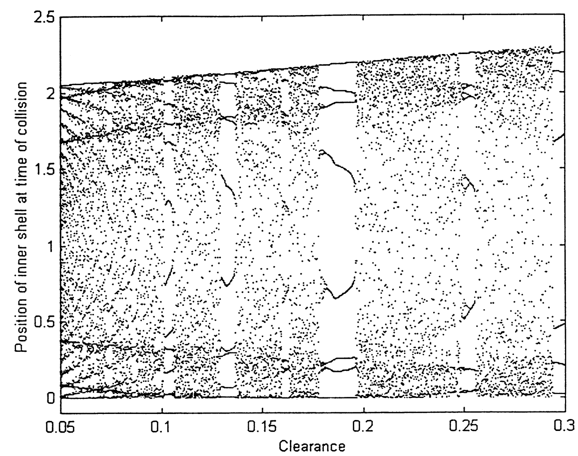

Figure 5. Response of system to changes in initial clearance.

amplitude does not appear to be generally valid for this nonlinear system.

2. Doubling the applied frequency roughly doubles the impact intensity **per cycle** (for the numerical example considered).

From this study it appears that an accelerated test criterion for this simple system could be developed if a damage accumulation model defined in terms of number of impacts and impact intensity could be defined.

7. SUMMARY

General procedures that have been developed for accelerating vibration tests have been summarized. The process of developing accelerated testing criteria can be defined in four steps as 1.) Assessment of Vibration Environments; 2.) Identification of Failure Mechanisms; 3.) Identification of a Damage Accumulation Rule and Specification of an Accelerated Test Sequence; and 4). Monitoring and Verification. Each step has its own inherent uncertainties. Very few papers reviewed make any mention of experimentally verifying the accuracy of the accelerated test procedure with regards to all but the simplest systems. Currently, applications to multi-component, multi-material systems with many interfaces appear to be beyond the capabilities of this technology. The example provided has shown that application to a very simple nonlinear system will be difficult because of the uncertainties in predicting the response of such a system to even a harmonic input. Clearly, more work is required in this area of vibration test technology if products are to be brought to market in a shorter time and with confidence that they have been tested to the appropriate and/or conservative simulated lifetime vibration environments.

8. ACKNOWLEDGEMENTS

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